The metallicity of the nebula surrounding the ultra-luminous X-ray source NGC 1313 X-2

E. Ripamonti[1],[⋆]**, M. Mapelli**[1]**, L. Zampieri**[2]**,** and **M. Colpi**[1]

[1] Dipartimento di Fisica 'G. Occhialini', Università di Milano-Bicocca, Piazza della Scienza 3, I–20126 Milano, Italy
[2] INAF-Osservatorio astronomico di Padova, Vicolo dell'Osservatorio 5, I–35122, Padova, Italy

Recent models of the formation of ultra-luminous X-ray sources (ULXs) predict that they preferentially form in low-metallicity environments. We look at the metallicity of the nebula surrounding NGC 1313 X-2, one of the best-studied ULXs. Simple estimates, based on the extrapolation of the metallicity gradient within NGC 1313, or on empirical calibrations (relating metallicity to strong oxygen lines) suggest a quite low metal content ($Z \sim 0.1\,Z_\odot$). But such estimates do not account for the remarkably strong X-ray flux irradiating the nebula. Then, we build photoionization models of the nebula using CLOUDY; using such models, the constraints on the metallicity weaken substantially, as we find $0.15\,Z_\odot \leq Z \leq 0.5\,Z_\odot$.

1 Introduction

The number of ultra-luminous X-ray sources (ULXs) in a galaxy appears to correlate with its star formation rate (SFR; see e.g. Irwin, Bregman & Athey 2004). Such correlation is reminiscent of the one between high-mass X-ray binaries (HMXBs) and SFR (e.g. Grimm, Gilfanov & Sunyaev 2003; Ranalli, Comastri & Setti 2003; Mineo, Gilfanov & Sunyaev 2010). On the other hand, in the last decade it has been suggested that ULXs correlate with low metallicities (Pakull & Mirioni 2002; Zampieri et al. 2004; Soria et al. 2005; Swartz, Soria & Tennant 2008). In fact, low metallicity would affect stellar evolution: it might increase the maximum stellar remnant mass (Mapelli, Colpi & Zampieri 2009; Zampieri & Roberts 2009; Mapelli et al. 2010a, hereafter M10), or increase the number and luminosity of HMXBs in more subtle ways (Linden et al. 2010). Indeed, M10 looked at the observational properties (number of ULXs, SFR, and metallicity Z) of a sample of galaxies, and found that metal-poor ($Z \lesssim 0.2 Z_\odot$) galaxies appear to host more ULXs than metal-rich galaxies with similar SFR (see also Mapelli et al. 2010b), even if the statistical significance of this result is low.

It must be remarked that studies such as M10 necessarily rely upon some *average* metallicity of each X-ray-observed galaxy, rather than on the metallicity of the ULXs themselves: otherwise, the sample would be far too small for any statistical analysis. However, metallicity variations within the same galaxy are well known: almost all the large spiral galaxies in our vicinity exhibit a metallicity gradient from the centre to the periphery (e.g. Pilyugin, Vílchez & Contini

2004); furthermore, even in smaller objects, or at fixed distances from the galactic centre, the spread in metallicities is often larger than the ~ 0.1 dex uncertainty typically associated with metallicity measurements. Then, it is important to determine the metallicity of ULXs (or at least of their immediate environments), since this would provide a more direct test of some of the models above (e.g., the model presented by M10 suggests that it is very difficult to form ULXs in environments with $Z \gtrsim 0.4\,Z_\odot$).

Unfortunately, the number of ULXs with known optical counterparts is very small; furthermore, spectroscopic observations of ULXs and/or their environments are available only for a handful of objects (NGC 1313 X-2, IC 342 X-1, Holmberg II X-1, among others; see e.g. Mucciarelli et al. 2005, Lehmann et al. 2005, Grisè, Pakull & Motch 2006, Abolmasov et al. 2007, Feng & Kaaret 2008), and often do not have a sufficient spectral coverage for a reliable metallicity estimate. In practice, the only object where such determination is possible with data in the literature is NGC 1313 X-2. Here we will aim to directly estimate the metallicity of the gaseous nebula surrounding such object.

2 The environment of NGC1313 X-2

NGC 1313 is a barred spiral at a distance of 3.7 Mpc (Tully 1988), with moderate SFR ($\simeq 1.4\,M_\odot\,\mathrm{yr}^{-1}$, as inferred from the Hα measurements of Ryder & Dopita 1994, using the Kennicutt 1998 conversion). It hosts 3 ULXs (Colbert et al. 1995), one of whom is a known supernova remnant. Observations by Pagel, Edmunds & Smith (1980), and by Hadfield & Crowther (2007) allow to determine the oxygen abun-

dances[1] of 8 HII regions with the reliable T_e method (e.g . Pilyugin 2001; Pilyugin & Thuan 2005 - herafter PT05). A linear fit to these metallicity data leads to a gradient

$$12+\log(O/H) = (8.52\pm0.13)-(0.55\pm0.25)(r/r_{25}), (1)$$

where r is the elliptical radius, and $r_{25} \simeq 4.56'$ is the optical semi-major axis of the galaxy (de Vaucouleurs et al. 1991); this corresponds to $Z \sim 0.4 Z_\odot$ at the centre, and $Z \sim 0.16 Z_\odot$ at the location of the outermost HII region used for the fit ($r \simeq 0.75 r_{25}$).

The source X-ray luminosity (0.3–10 keV) is known to vary in the 2–$30 \times 10^{39}\,\mathrm{erg\,s^{-1}}$ range. The X-ray emission is generally fit with a multicolor disk (MCD, with kT_{MCD} varying in the 0.13–0.25 keV range) plus power law (PL, with photon index varying between 1.7 and 2.5) spectrum, with the energy in the MCD component representing a fraction 0.46–0.94 of the energy in the PL component; such spectrum is then absorbed by a column density $N_{\mathrm{H,t}}$ in the 2–$4\times10^{21}\,\mathrm{cm^{-2}}$ range (e.g. Zampieri et al. 2004, Feng & Kaaret 2006, Mucciarelli et al. 2007, and references therein), much larger than the galactic absorption towards NGC 1313 ($N_{\mathrm{H,g}} \simeq 4 \times 10^{20}\,\mathrm{cm^{-2}}$, Dickey & Lockman 1990).

The optical counterpart to NGC1313 X-2 has been identified as object C1 (Pakull, Grisé & Motch 2006, Mucciarelli et al. 2007, Liu et al. 2007), using HST and VLT observations. Assuming E(B-V)$\sim$0.1 (Mucciarelli et al. 2007, Grisé et al. 2008)[2], the object absolute V magnitude is $M_{\mathrm{V}} \simeq -4.6 \pm 0.2$, and its blue color ($B - V = -0.13 \pm 0.06$) suggests an high effective temperature (20000 K$\leq T_{\mathrm{eff}} \leq$ 30000 K). This is surrounded by an OB association (about 20 Myr old), and by a large ionized nebula (about 500×300 pc in size; cfr. Grisé et al. 2008). Remarkably, the optical luminosity of object C1 appears to vary with a periodicity of ~ 6.1 days (Liu, Bregman & McClintock 2009). Such result is still uncertain (e.g. Impiombato et al. 2010), but suggests that the accreting object is a black hole with $M \sim$ 50–100 $\mathrm{M}_\odot$ (Patruno & Zampieri 2010).

3 Simple metallicity estimates

NGC 1313 X-2 is located about 6 arcmin south of the centre of NGC1313, corresponding to $r \simeq 1.5 r_{25}$: eq. (1) would imply 12+log(O/H)=7.69 $\pm$ 0.40, i.e $Z \simeq 0.06^{+0.09}_{-0.04} Z_\odot$.

In order to test this result, we looked at the VLT spectrum of the optical counterpart of NGC1313 X-2 presented in Mucciarelli et al. (2005). In order to extract the nebular continuum, we looked specifically at those positions along the slit which are close to NGC 1313 X-2, but where no stellar emission can be detected. In Table 1 we list the emission lines we were able to confidently detect; the typical detection limit was at about $0.2I(\mathrm{H}\beta)$. It should be noted that

Table 1 List of detected emission lines.

Ion	$\lambda(\text{Å})^{\mathrm{a}}$	$I(\text{line})/I(\mathrm{H}\beta)^{\mathrm{b}}$
OII	3727	6.03 ± 1.34
HI (Hδ)	4102	0.38 ± 0.16
HI (Hγ)	4340	0.56 ± 0.16
HI (Hβ)	4861	$1.00 \pm 0.17^{\mathrm{c}}$
OIII	4959	0.47 ± 0.15
OIII	5007	1.69 ± 0.36
OI	6300	$0.93^{+0.23}_{-0.46}{}^{\mathrm{d}}$
NII	6548	$0.12 \pm 0.10^{\mathrm{d}}$
HI (Hα)	6563	$3.10 \pm 0.70^{\mathrm{e}}$
NII	6584	$0.53 \pm 0.30^{\mathrm{d}}$
SII	6725	1.95 ± 0.42

[a] Rest-frame wavelength. [b] Ratio of de-reddened fluxes; the de-reddening was performed by imposing that I(Hα)/I(Hβ)=3.1 (cfr. Osterbrock 1989). Quoted errors include uncertainties on the line itself, on the normalization - i.e. on I(Hβ) - and on the reddening, unless differently specified. [c] Error bars include only the uncertainty on the line itself. [d] Error bars include an additional component due to the removal of the blending of lines. [e] Error bars include uncertainties in the line itself, in the normalization to I(Hβ), and in the de-blending.

several emission lines exhibit significant variations along the slit, so that the intensity ratios in Table 1 are the result of spatial averaging.

Since we were unable to observe the weak OIII $\lambda = 4363$ Å line, the simplest way to estimate the metallicity of the nebula is to use the P and ff methods described by PT05, relying only upon the intensities of strong oxygen lines (i.e. the indexes $R_2 \equiv I(\text{OII}3727)/I(\mathrm{H}\beta) \simeq 6.03$, $R_3 \equiv [I(\text{OIII}4959) + I(\text{OIII}5007)]/I(\mathrm{H}\beta) \simeq 2.16$, their sum $R_{23} \equiv R_2 + R_3 \simeq 8.19$, and the ratio $P \equiv R_3/R_{23} \simeq 0.26$). In this case, the P method fails, since the object falls in the "gap" between the high-Z and the low-Z branches of the P calibration (a fact weakly suggesting that $8.0 \lesssim 12 + \log(\mathrm{O/H}) \lesssim 8.25$, i.e. $0.12 Z_\odot \lesssim Z \lesssim 0.21 Z_\odot$); instead, the ff method gives $12 + \log(\mathrm{O/H}) \simeq 7.90$, or $Z \simeq 0.10 Z_\odot$.

However, such metallicity is very uncertain, not only because the results of the P and the ff methods are (slightly) inconsistent, but especially because both methods were calibrated with *normal* HII regions, where ionization is (almost) completely due to UV photons emitted by O-B stars. Instead, in this case we know that the nebula is in the immediate vicinity of a very intense X-ray source, so that a significant fraction of the ionization might be collisional, as it is induced by much harder photons (in fact, the bulk of the ionizations are due to the collisions involving the energetic photo-electrons produced by the X-ray photons). Furthermore, the edge of normal HII regions is much sharper than that of X-ray ionized nebulae, since X-ray photons can travel much farther than UV photons in a neutral gas: as a result, there is a large volume with moderate (0.1–0.9) ionization fraction, producing unusually strong OI $\lambda = 6300$ Å emission. Such line is indeed observed, even if shocks might provide a further (or alternative) explanation for its strength.

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[1] The quantity 12+log(O/H) is generally used as a proxy for total metallicity; in this notation a metallicity $Z = Z_\odot \equiv 0.02$ corresponds to 12+log(O/H)=8.92.

[2] Liu et al. (2007) suggested E(B-V)$\sim$0.3, but according to Patruno & Zampieri (2010) such value is incompatible with other observed properties.

Table 2 Parameter space explored by the CLOUDY models.

Parameter	List of values
T_* [K]	26200, 30000, 31000, 32000, 33500, 35000, 40000, 45000
$N_{H,i}$ [10^{21} cm^{-2}]	0.01, 0.03, 0.1, 0.3, 1., 2.
12+log(O/H)	9.22, 8.92, 8.82, 8.72, 8.62, 8.52, 8.42, 8.32, 8.22, 8.12, 7.92, 7.62, 7.32
[N/O]	0, -0.5
[dust/metal]	0, -1
$\log(n_H)$ [cm^{-3}]	0, 0.5, 1, 1.5, 2
L_X [erg s^{-1}]	6×10^{39}
kT_{MCD} [keV]	0.2
Γ_{PL}	2.0
F_{MCD}/F_{PL}	0.8
$N_{H,t}$ [10^{21} cm^{-2}]	3.0
$N_{H,g}$ [10^{21} cm^{-2}]	0.4
f_f	1/3
R_{in} [pc]	1

T_* is the effective temperature of the companion star; its ionizing flux was varied accordingly, as in Tab. 2.3 of Osterbrock (1989). $N_{H,i}$ is the column density which is crossed by the radiation before entering the nebula (i.e., within the source or in its immediate vicinity). 12+log(O/H) is the nebula oxygen abundance, and indicates the general metallicity, as we assume the ratio X/O of any metal X (except N) to remain equal to the solar value. [N/O]$\equiv \log[(N/O)/(N/O)_\odot]$, and [dust/metal] is defined in the same way, but with reference to the dust/metal ratio in Orion, rather than in the Sun. n_H is the hydrogen number density in the nebula. L_X is the unabsorbed X-ray luminosity in the 0.3–10 keV spectral range. kT_{MCD}, Γ_{PL}, and F_{MCD}/F_{PL} are the temperature of the multi-color disk, the power-law photon index, and the ratio of the energy emitted in the two components, respectively. $N_{H,t}$ and $N_{H,g}$ are the total column density from the X-ray source to the observer, and the column density due to absorption in our Galaxy, respectively. Finally, f_f is the filling factor, and R_{in} is the distance of the inner "edge" of the nebula from the X-ray source.

4 Photoionization models

Since "standard" line strength-metallicity calibrations (such as the ones in PT05) are likely inappropriate for this object, we used the public code CLOUDY (version 08.00; see Ferland et al. 1998) in order to build a grid of photoionization models of the nebula, and then compare the prediction of these models to the observed spectrum[3].

Table 2 illustrates the region of parameter space covered by the ~ 12000 photoionization models of the grid. We explored variations in the spectrum and luminosity of the companion star[4], in the intrinsic absorption of the X-ray spectrum (which was assumed to be negligible at photon energies below 54.4 eV), in the metallicity of the gas (mainly expressed by the oxygen abundance), in the N/O and dust/metal ratios, and in the density of the nebula. Other

Table 3 Comparison of observations and models.

Model	OII	OIII	OI	NII	SII
A	5.76	2.60	0.87	0.59	1.45
	-0.20σ	$+0.99\sigma$	-0.12σ	-0.21σ	-1.19σ
B	5.77	2.04	0.60	1.27	1.90
	-0.20σ	-0.27σ	-0.71σ	$+2.39\sigma$	-0.12σ

For each model, in the first line we report the sum of the predicted intensities (normalized to Hβ) of the lines of each ion which are listed in Table 1; in the second line we report the difference between observed values and model predictions, in terms of the observational uncertainty (σ).

quantities (such as the X-ray luminosity L_X) were kept constant at their observed values (or, when they are known to vary, at reasonable averages of the observed values), or at "typical" values observed in other HII region (e.g. the filling factor). Finally, we assumed the nebula to be a spherical corona centered on the X-ray source, with an arbitrary inner radius R_{in}, and an outer radius which is set by the relation

$$R_{out} = R_{in} + \frac{N_{H,t} - N_{H,i} - N_{H,g}}{n_H\, f_f\, (Z/Z_\odot)}. \qquad (2)$$

By comparing the model predictions with the observations (we actually ranked our models, with "scores" assigned with a procedure similar to the one used to estimate the χ^2 statistics[5]), we found that a very good agreement could be obtained with model A (cfr. Table 3). In such model, $T_* = 40000$ K, $N_{H,i} = 10^{20}$ cm^{-2}, $12 + \log(O/H) = 8.22$ (i.e. $Z = 0.2\,Z_\odot$), [N/O]=-0.5, [dust/metal]=-1, $n_H = 1$ cm^{-3}. Apart from moderate ($\sim 1\sigma$) discrepancies for the OIII and SII lines, the main problem of this model is an over-prediction of the radius of the HII region (~ 400 pc); but the overall agreement is quite good.

However, there is an ample range of models with good overall agreement. For example, in Table 3 we show the result for a second model, quite different from model A. In fact, model B was calculated with $T_* = 35000$ K, $N_{H,i} = 3 \times 10^{20}$ cm^{-2}, $12 + \log(O/H) = 8.92$ (i.e. $Z = Z_\odot$), [N/O]=-0.5, [dust/metal]=-1, $n_H = 1$ cm^{-3}. There is excellent agreement in all the lines except the NII ones, which are significantly ($\geq 2\sigma$) over-predicted (instead, the radius of the HII region is predicted to be ~ 150 pc).

When we marginalize over all the free parameters, we infer that both [N/O] and [dust/metal] must be significantly smaller than 0 (no model with [N/O]=0 can be considered satisfactory; the effects of [dust/metal]=0 are less dramatic, but in *all* the comparisons of pairs of models differing only for this quantity, the low-dust one is better than the high-dust case). With similar arguments, we find that $35000 \lesssim T_*/K \lesssim 40000$, $0.1 \lesssim N_{H,i}/(10^{21}\,cm^{-2}) \lesssim 0.3$, and $1 \lesssim n_H/(cm^{-3}) \lesssim 10$. Unfortunately, the less constraining result is the one about the metallicity, as we find that there exist satisfactory models for $8.12 \lesssim 12 + \log(O/H) \lesssim 8.92$ (i.e. for $0.15 \leq Z/Z_\odot \leq 1$).

The metallicity result can be improved by remarking that theoretical considerations on the production of N (e.g.

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[3] We note that (differently from the MAPPINGS code - see e.g. Sutherland & Dopita 1993, and Allen et al. 2008), CLOUDY does not account for shocks. This might affect our results, so that we plan to extend this work by using MAPPINGS in the near future.

[4] Each of the values of the effective stellar temperature T_* is paired to the UV luminosity of a star of the corresponding spectral type; spectra were based on stellar atmospheres from a library built with the ATLAS9 code (Castelli & Kurucz 2004) where we assumed that the metallicity of the companion star is equal to that of the nebula.

[5] However, such "scores" do not enjoy the properties of χ^2 statistics.

Matteucci 1986) suggest that, while some N is of "primary" origin (i.e. it can be produced directly from metal-free stars), it is also a "secondary" element (i.e., its production requires the presence of other metals). Such fact implies that (N/O) should positively correlate with (O/H), as is actually observed (e.g. Pilyugin, Thuan & Vílchez 2003). Indeed, if we look at fig. 3 of Pilyugin et al. 2003, we see that no HII region has been observed with both 12+log(O/H) $\gtrsim$ 8.62 (i.e. $Z \gtrsim 0.5 Z_\odot$) and [N/O] $\lesssim$ -0.5. Then, the "satisfactory" models with $Z \gtrsim 0.5 Z_\odot$ are likely unphysical, since all of them have [N/O]=-0.5.

5 Summary and conclusions

We investigated the metal abundance in the nebula surrounding the ULX source NGC 1313 X-2 by building detailed photoionization models with CLOUDY, and comparing their predictions to observational data. The resulting metallicity, $Z \sim 0.2^{+0.3}_{-0.05} Z_\odot$, and especially its upper limit, is quite higher than what could be inferred from simpler methods (both the metallicity gradient in NGC 1313, and the simple metallicity calibrations suggest $Z \sim 0.1 Z_\odot$). This might partially derive from the known discrepancy between "empirical" and "model" abundances (see e.g. the discussion at the end of Moustakas et al. 2010), but more likely reflects the inadequacy of empirical calibrations in environments where the ionization is due to the radiation emitted by an X-ray source, rather than normal stars.

Other possible sources of error are i) the possible presence of shocks (Pakull et al. 2010, and Russel et al. 2010 showed that shocks exist at least in some of the nebulae surrounding ULXs), and ii) the fact that the optical-UV spectrum of the counterpart of NGC 1313 X-2 is likely different from that of a normal star, because it definitely includes a component due to the reprocessing of the X-ray radiation (e.g. Patruno & Zampieri 2008,2010). In the near future we plan to extend our analysis, including both these effects.

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